Flip Tanedo
UC Riverside Particle Theory

3 Feb 2017 Washington D.C.
APS Topical Group on Hadronic Physics
Astro + Cosmo: Dark Matter Exists

GALACTIC ROTATION CURVES

GRAVITATIONAL LENSING

COSMIC MICROWAVE BACKGROUND

Standard Model is **not** complete

Images: Jeff Filippini (Berkeley Cosmology 2005), NASA APOD 2006, NASA WMAP
Weakly-Interacting Massive Particles

INTERACTS VIA WEAK FORCE (W and Z BOSONS)

Explains: Why is there so much dark matter around?

"WEAK SCALE" MASS
\(\sim 100 \text{ GeV}\)

\[ \chi \]

SM

WEAK FORCE

\[ \chi \]

SM

OBSERVED AMOUNT OF DARK MATTER TODAY

\[ \Omega_{\chi} h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma_{\text{ann}} v \rangle} \]

"WEAK SCALE" ANNIHILATION RATE

dark matter annihilation vs. expansion of universe
WIMP Complementarity

Dark matter searches related by crossing symmetry:

- **INDIRECT**
  - Dark Matter\(\chi\) to Standard Model\(\text{sm}\) to Dark Matter\(\chi\)

- **DIRECT**
  - Direct detection: Dark Matter\(\chi\) to Standard Model\(\text{sm}\)

- **COLLIDER**
  - Collider: Standard Model\(\text{sm}\) to Dark Matter\(\chi\)

 Exceptions: e.g. SIMP Miracle (1402.5143); D M d m (1312.2618); Agashe, Cui, et al. (1405.7370). See talk by Yanou Cui.
Tough Times for WIMPs
WIMP Searches vs. Light Mediators

Dark Matter  Mediator  Standard Model

χ ↔ A'  χ ↔ A'  q ↔ q

INDIRECT  DIRECT  COLLIDER

can keep thermal relic!
Renormalizable Portals

Dark Matter $\rightarrow$ Mediator $\rightarrow$ Higgs $\rightarrow$ Standard Model

Dark Matter $\rightarrow$ Mediator $\rightarrow$ $\nu_R$ $\rightarrow$ Standard Model

BENCHMARK IN THIS TALK

Dark Matter $\rightarrow$ $U(1)'$ $\rightarrow$ Kinetic Mixing $\rightarrow$ Standard Model

... plus variations of each portal
New Searches with Light Mediators

**Dark Matter** → **Mediator** → **Standard Model**

**INDIRECT**

- A' → N

- A' → N

**DIRECT**

- A' → N

- A' → N

**MEDIATOR PRODUCTION**

- SM → A' → SM

- SM → A' → SM

**accelerators**

**astro**

**Halo Morphology:**

• Milky Way

- Standard Model

- Dark Matter

- Mediator

- accelerators

- astro

- Standard Model

- Dark Matter

- Mediator

- Halo Morphology:
Step 1: Mediator Production

EXAMPLES OF LIGHT MEDIATOR PRODUCTION STRATEGIES

- annihilation
- bremsstrahlung
- meson decay

Others: Drell-Yan, nuclear transitions, Higgs decays, …
Step 2: Mediator Decay

Adapted from Natalia Toro, Dark Sectors 2017 (1608.03591)
Interpretation with Standard Model

Mediation Mass

**LIMITED BY STATISTICS**

 existing bounds

**_LIMITED BY VERTEXING**

displaced vertex

Adapted from 1608.08632, 1608.03591, N. Toro at Dark Sectors 2017
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lab</th>
<th>Production</th>
<th>Detection</th>
<th>Vertex</th>
<th>Mass (MeV)</th>
<th>Mass Res. (MeV)</th>
<th>Beam</th>
<th>Ebeam (GeV)</th>
<th>Ibeam or Lumi</th>
<th>Machine</th>
<th>1st Run</th>
<th>Next Run</th>
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<tbody>
<tr>
<td>APEX</td>
<td>JLab</td>
<td>e-brem</td>
<td>$\ell^+\ell^-$</td>
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<td>65 – 600</td>
<td>0.5%</td>
<td>$e^-$</td>
<td>1.1–4.5</td>
<td>150 $\mu$A</td>
<td>CEBAF(A)</td>
<td>2010</td>
<td>2018</td>
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<tr>
<td>A1</td>
<td>Mainz</td>
<td>e-brem</td>
<td>$e^+e^-$</td>
<td>no</td>
<td>40 – 300</td>
<td>?</td>
<td>$e^-$</td>
<td>0.2–0.9</td>
<td>140 $\mu$A</td>
<td>MAMI</td>
<td>2011</td>
<td>-</td>
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<td>HPS</td>
<td>JLab</td>
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<td>$e^+e^-$</td>
<td>yes</td>
<td>20 – 200</td>
<td>1–2</td>
<td>$e^-$</td>
<td>1–6</td>
<td>50–500 nA</td>
<td>CEBAF(B)</td>
<td>2015</td>
<td>2018</td>
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<tr>
<td>DarkLight</td>
<td>JLab</td>
<td>e-brem</td>
<td>$e^+e^-$</td>
<td>no</td>
<td>&lt; 80</td>
<td>?</td>
<td>$e^-$</td>
<td>0.1</td>
<td>10 mA</td>
<td>LERF</td>
<td>2016</td>
<td>2018</td>
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<tr>
<td>MAGIX</td>
<td>Mainz</td>
<td>e-brem</td>
<td>$e^+e^-$</td>
<td>no</td>
<td>10 – 60</td>
<td>?</td>
<td>$e^-$</td>
<td>0.155</td>
<td>1 mA</td>
<td>MESA</td>
<td>2020</td>
<td>-</td>
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<tr>
<td>NA64</td>
<td>CERN</td>
<td>e-brem</td>
<td>$e^+e^-$</td>
<td>no</td>
<td>1 – 50</td>
<td>?</td>
<td>$e^-$</td>
<td>100</td>
<td>$2 \times 10^{11}$ EOT/yr</td>
<td>SPS</td>
<td>2017</td>
<td>2022</td>
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<tr>
<td>Super-HPS</td>
<td>SLAC</td>
<td>e-brem</td>
<td>vis</td>
<td>yes</td>
<td>&lt; 500</td>
<td>?</td>
<td>$e^-$</td>
<td>4 – 8</td>
<td>1 $\mu$A</td>
<td>DASEL</td>
<td>?</td>
<td>?</td>
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<tr>
<td>(TBD)</td>
<td>Cornell</td>
<td>e-brem</td>
<td>$e^+e^-$</td>
<td>?</td>
<td>&lt; 100</td>
<td>?</td>
<td>$e^-$</td>
<td>0.1–0.3</td>
<td>100 mA</td>
<td>CBETA</td>
<td>?</td>
<td>?</td>
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<tr>
<td>VEPP3</td>
<td>Budker</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>5 – 22</td>
<td>1</td>
<td>$e^+$</td>
<td>0.500</td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>VEPP3</td>
<td>2019</td>
<td>?</td>
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<tr>
<td>PADME</td>
<td>Frascati</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>1 – 24</td>
<td>2–5</td>
<td>$e^+$</td>
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<td>$&lt; 10^{14}$ e$^{-}$OT/y</td>
<td>Linac</td>
<td>2018</td>
<td>?</td>
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<tr>
<td>MMAPS</td>
<td>Cornell</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>20 – 78</td>
<td>1–6</td>
<td>$e^+$</td>
<td>6.0</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>Synchr</td>
<td>?</td>
<td>?</td>
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<tr>
<td>KLOE 2</td>
<td>Frascati</td>
<td>several</td>
<td>vis/invis</td>
<td>no</td>
<td>&lt; 1.1 GeV</td>
<td>1.5</td>
<td>$e^+e^-$</td>
<td>0.51</td>
<td>$2 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
<td>DA$\phi$NE</td>
<td>2014</td>
<td>-</td>
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<tr>
<td>Belle II</td>
<td>KEK</td>
<td>several</td>
<td>vis/invis</td>
<td>no</td>
<td>$\lesssim$ 10 GeV</td>
<td>1–5</td>
<td>$e^+e^-$</td>
<td>$4 \times 7$</td>
<td>1 $\sim 10$ ab$^{-1}$/y</td>
<td>Super-KEKB</td>
<td>2018</td>
<td>-</td>
</tr>
<tr>
<td>SeaQuest</td>
<td>FNAL</td>
<td>several</td>
<td>$\mu^+\mu^-$</td>
<td>yes</td>
<td>$\lesssim$ 10 GeV</td>
<td>3–6%</td>
<td>p</td>
<td>120</td>
<td>$10^{18}$ POT/yr</td>
<td>MI</td>
<td>2017</td>
<td>2020</td>
</tr>
<tr>
<td>SHIP</td>
<td>CERN</td>
<td>several</td>
<td>vis</td>
<td>yes</td>
<td>$\lesssim$ 10 GeV</td>
<td>1–2</td>
<td>p</td>
<td>400</td>
<td>$2 \times 10^{20}$ POT/5y</td>
<td>SPS</td>
<td>2026</td>
<td>-</td>
</tr>
<tr>
<td>LHCb</td>
<td>CERN</td>
<td>several</td>
<td>$\ell^+\ell^-$</td>
<td>yes</td>
<td>$\lesssim$ 40 GeV</td>
<td>$\sim$ 4</td>
<td>pp</td>
<td>6500</td>
<td>$\sim 10$ fb$^{-1}$/y</td>
<td>LHC</td>
<td>2010</td>
<td>2015</td>
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</tbody>
</table>
## Other Searches for Mediators

<table>
<thead>
<tr>
<th>INTERACTION</th>
<th>WIMP SEARCH</th>
<th>LIGHT MEDIATORS</th>
<th>EXAMPLES OF NOVEL SEARCHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCTION</td>
<td>COLLIDER: MISSING ENERGY</td>
<td>BEAM DUMP, FIXED-TARGET, MESON DECAY</td>
<td>NUCLEAR TRANSITIONS</td>
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<tr>
<td>SCATTERING</td>
<td>DIRECT DETECTION</td>
<td>RECOIL SPECTRUM</td>
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<tr>
<td>ANNIHILATION</td>
<td>INDIRECT DETECTION</td>
<td>ANNIHILATION TO ON-SHELL MEDIATORS</td>
<td>CAPTURE &amp; ENHANCED ANNIH.</td>
</tr>
<tr>
<td>SELF-INT.</td>
<td>N/A</td>
<td>HALO PROFILE</td>
<td>DISK STABILITY</td>
</tr>
</tbody>
</table>

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**DARK SECTORS**
Example: Earth Capture

WIMPs are never in equilibrium
Mediators change everything

\[ \dot{N}_\chi = C_{\text{cap}} - C_{\text{ann}} N_\chi^2 \]

Feng, Smolinsky, Tanedo (1509.07525)

\[ \tau = \frac{1}{\sqrt{C_{\text{cap}} C_{\text{ann}}}} \]
Conclusion

Light mediators avoid the tightest WIMP bounds while offering new search opportunities

Well motivated (renormalizable portals), permits thermal freeze out, compatible with many classes of new physics…

REFERENCE AND UPCOMING WORKSHOP

- Useful reference: 1608.08632 (Dark Sectors 2016 report)

OTHER DIRECTIONS BEYOND A VANILLA WIMP

primordial black holes (no new DM particle), low-mass/axion/axion-like dark matter, asymmetric dark matter, non-thermal/freeze-in, strongly interacting massive particles (3-to-2 annihilation), inelastic, different spins, strong dynamics, …
EFT vs. Simplified Model

Adapted from Tim Tait, UCLA DM 2016